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Abstract

We calculate the electromagnetic (EM) form fators of the pseudoscalar mesons in the light-front framework. Specially, these form factors are extracted from the relevant matrix elements directly, instead of choosing the Breit frame. The results show that the charge radius of the meson are related to both the first and second longitudinal momentum square derivative of the momentum distribution function. The static properties of the EM form factors and the heavy quark symmetry of the charge radii are checked analytically when we take the heavy quark limit. In addition, we use the Gaussia-type wave function to obtain the numerical results.

1 Introduction

The understanding of the electromagnetic (EM) properties of hadrons is an important topic, and the EM form factors which are calculated within the non-petrturbative methods are the useful tool for this purpose. There have been numerous experimental [1-7] and theoretical studies [8-12] of the EM form factors of the light pseudoscalar meson (π ana K). However, duing to the experiments are more difficult, the EM form factors of the light vector meson (ρ and K^*) have fewer investigations than their pseudoscalar counterparts [13, 14], even though they could provide much information about the bound-state dynamics. As for the EM form factors of the heavy mesons (which containing one heavy quark), there are much fewer study than the light ones. In the heavy hadron investigation, however, the heavy quark symmetry (HQS) [15] is a fundamental and model-independent property. In this work, we will study the EM form factors of the light and heavy pseudoscalar mesons with the light-front framework, and will check whether HQS is satisified or not among these EM properties of the heavy meson.

Light front quark model (LFQM) is the only relativistic quark model in which a consistent and fully relativistic treatment of quark spins and the center-of-mass motion can be carried out. Thus it has been applied in the past to calculate various form factors [16-22]. This model has many advantages. For example, the light-front wave function is manifestly boost invariant as it is expressed in terms of the momentum fraction variables (in "+" component) in analog to the parton distributions in the infinite momentum frame. Moreover, hadron spin can also be relativistically constructed by using the so-called Melosh rotation [23]. The kinematic subgroup of the light-front formalism has the maximum number of interaction-free generators including the boost operator which describes the center-of-mass motion of the bound state (for a review of the light-front dynamics and light-front QCD, see [24]).

The paper is organized as follows. In Sec. 2, the basic theoretical formalism is given and the decay constant and the EM form factors are derived for pseudoscalar mesons. In Sec. 3, we take the heavy quark limit to check whether HQS is satisfied or not. Sec. 4, the numerical result are obtained by choosing the Gaussian-type wave function. Finally, a conclusion is given in Sec. 5.

2 Framework

A meson bound state consisting of a quark q_1 and an antiquark $\bar{q}_2$ with total momentum P and spin S can be written as

$$\begin{aligned} |M(P,S,S_z)\rangle &= \int \{d^3p_1\}\{d^3p_2\}\ 2(2\pi)^3\delta^3(\tilde{P}-\tilde{p}_1-\tilde{p}_2) \\ &\quad \times \sum_{\lambda_1,\lambda_2} \Psi^{SS_z}(\tilde{p}_1,\tilde{p}_2,\lambda_1,\lambda_2)\ |q_1(p_1,\lambda_1)\bar{q}_2(p_2,\lambda_2)\rangle, \end{aligned} \tag{1}$$

where p_1 and p_2 are the on-mass-shell light-front momenta,

$$\tilde{p} = (p^+, p_\perp)\ , \quad p_\perp = (p^1, p^2)\ , \quad p^- = \frac{m^2+p_\perp^2}{p^+}, \tag{2}$$

and

$$
\begin{aligned}
&\{d^3p\} \equiv \frac{dp^+ d^2p_\perp}{2(2\pi)^3}, \\
&|q(p_1,\lambda_1)\bar{q}(p_2,\lambda_2)\rangle = b^\dagger_{\lambda_1}(p_1) d^\dagger_{\lambda_2}(p_2)|0\rangle, \\
&\{b_{\lambda'}(p'), b^\dagger_\lambda(p)\} = \{d_{\lambda'}(p'), d^\dagger_\lambda(p)\} = 2(2\pi)^3\ \delta^3(\tilde{p}' - \tilde{p})\ \delta_{\lambda'\lambda}.
\end{aligned} \tag{3}
$$

In terms of the light-front relative momentum variables $(x, k_\perp)$ defined by

$$
\begin{aligned}
&p_1^+ = (1-x)P^+, \quad p_2^+ = xP^+, \\
&p_{1\perp} = (1-x)P_\perp + k_\perp, \quad p_{2\perp} = xP_\perp - k_\perp,
\end{aligned} \tag{4}
$$

the momentum-space wave-function Ψ^{SS_z} can be expressed as

$$
\Psi^{SS_z}(\tilde{p}_1, \tilde{p}_2, \lambda_1, \lambda_2) = R^{SS_z}_{\lambda_1\lambda_2}(x, k_\perp)\ \phi(x, k_\perp), \tag{5}
$$

where $\phi(x, k_\perp)$ describes the momentum distribution of the constituents in the bound state, and $R^{SS_z}_{\lambda_1\lambda_2}$ constructs a state of definite spin (S, S_z) out of light-front helicity (λ_1, λ_2) eigenstates. Explicitly,

$$
R^{SS_z}_{\lambda_1\lambda_2}(x, k_\perp) = \sum_{s_1,s_2} \langle\lambda_1|\mathcal{R}^\dagger_M(1-x, k_\perp, m_1)|s_1\rangle\langle\lambda_2|\mathcal{R}^\dagger_M(x, -k_\perp, m_2)|s_2\rangle\langle\frac{1}{2}s_1; \frac{1}{2}s_2|S, S_z\rangle, \tag{6}
$$

where $|s_i\rangle$ are the usual Pauli spinors, and $\mathcal{R}_M$ is the Melosh transformation operator [23]:

$$
\mathcal{R}_M(x, k_\perp, m_i) = \frac{m_i + xM_0 + i\vec{\sigma}\cdot\vec{k}_\perp \times \vec{n}}{\sqrt{(m_i + xM_0)^2 + k_\perp^2}}, \tag{7}
$$

with $\vec{n} = (0, 0, 1)$, a unit vector in the z-direction, and

$$
M_0^2 = \frac{m_1^2 + k_\perp^2}{(1-x)} + \frac{m_2^2 + k_\perp^2}{x}. \tag{8}
$$

In practice it is more convenient to use the covariant form for $R^{SS_z}_{\lambda_1\lambda_2}$ [17]:

$$
R^{SS_z}_{\lambda_1\lambda_2}(x, k_\perp) = \frac{\sqrt{p_1^+ p_2^+}}{\sqrt{2}\ \widetilde{M}_0}\ \bar{u}(p_1, \lambda_1)\Gamma v(p_2, \lambda_2), \tag{9}
$$

where

$$
\begin{aligned}
&\widetilde{M}_0 \equiv \sqrt{M_0^2 - (m_1 - m_2)^2}, \\
&\Gamma = \gamma_5 \qquad (\text{pseudoscalar}, S = 0).
\end{aligned}
$$

We normalize the meson state as

$$
\langle M(P', S', S_z')|M(P, S, S_z)\rangle = 2(2\pi)^3 P^+ \delta^3(\tilde{P}' - \tilde{P})\delta_{S'S}\delta_{S_z'S_z}\ , \tag{10}
$$

so that the normalization condition of the momentum distribution function can be obtained

$$\int \{dx\}\ |\phi(x,k_\perp)|^2 = 1. \tag{11}$$

where

$$\{dx\} \equiv \frac{dx\,d^2k_\perp}{2(2\pi)^3}$$

In principle, the momentum distribution amplitude $\phi(x,k_\perp)$ can be obtained by solving the light-front QCD bound state equation [24]. However, before such first-principles solutions are available, we would have to be contented with phenomenological amplitudes. One example that has been often used in the literature for heavy mesons is the Gaussian-type wave function,

$$\phi(x,k_\perp)_{\rm G} = \mathcal{N}\sqrt{\frac{dk_z}{dx}}\ \exp\left(-\frac{\vec{k}^2}{2\omega^2}\right), \tag{12}$$

where $\mathcal{N} = 4(\pi/\omega^2)^{3/4}$ and k_z is of the internal momentum $\vec{k} = (\vec{k}_\perp, k_z)$, defined through

$$1-x = \frac{e_1 - k_z}{e_1+e_2}, \qquad x = \frac{e_2+k_z}{e_1+e_2}, \tag{13}$$

with $e_i = \sqrt{m_i^2 + \vec{k}^2}$. We then have

$$M_0 = e_1 + e_2, \qquad k_z = \frac{xM_0}{2} - \frac{m_2^2 + k_\perp^2}{2xM_0}, \tag{14}$$

and

$$\frac{dk_z}{dx} = \frac{e_1 e_2}{x(1-x)M_0}, \tag{15}$$

which is the Jacobian of transformation from $(x,k_\perp)$ to $\vec{k}$.

2.1 Decay Constants

The decay constants of pseudoscalar mesons $P(q_1\bar{q}_2)$ are defined by

$$\langle 0|A_\mu|P(p)\rangle = i\,f_P\,p_\mu, \tag{16}$$

where A_μ is the axial vector current. It can be evaluated using the light-front wave function given by (12)

$$\begin{aligned}\langle 0|\bar{q}_2\gamma^+\gamma_5 q_1|P\rangle \;&=\; \int \{d^3p_1\}\{d^3p_2\}2(2\pi)^3\delta^3(\tilde{p}-\tilde{p}_1-\tilde{p}_2)\phi_P(x,k_\perp)R^{00}_{\lambda_1\lambda_2}(x,k_\perp)\\ &\quad\times\langle 0|\bar{q}_2\gamma^+\gamma_5 q_1|q_1\bar{q}_2\rangle.\end{aligned} \tag{17}$$

Since $\widetilde{M}_0\sqrt{x(1-x)} = \sqrt{\mathcal{A}^2 + k_\perp^2}$, it is straightforward to show that

$$f_P = 4\frac{\sqrt{3}}{\sqrt{2}}\int \{dx\}\,\frac{\phi_P(x,k_\perp)}{\sqrt{\mathcal{A}^2+k_\perp^2}}\,\mathcal{A}, \tag{18}$$

where $\mathcal{A} = m_1 x + m_2(1-x)$. Note that the factor $\sqrt{3}$ in (18) arises from the color factor implicitly in the meson wave function.

2.2 EM Form Factors

The EM form factor of a meson P is determined by the scattering of one virtual photon and one meson. Since the momentum of the virtual photon q is space-like, it is always possible to orient the axes in such a manner that $Q^+ = 0$. Thus the EM form factor of a pseudoscalar meson P is determined by the matrix element

$$\langle P(P')|J^+|P(P)\rangle = e\ F_P(Q^2)(P+P')^+, \tag{19}$$

where $J^\mu = \bar{q} e_q e \gamma^\mu q$ is the vector current, e_q is the charge of quark q in e unit, and $Q^2 = -(P'-P)^2 \geq 0$. With LFQM, F_P can be extracted by Eq. (19)

$$\begin{aligned} F_P(Q^2) &= e_{q_1}\int\{dx\}\frac{\phi_P(x,k_\perp)}{\sqrt{\mathcal{A}^2+k_\perp^2}}\frac{\phi_{P'}(x,k'_\perp)}{\sqrt{\mathcal{A}^2+k'^2_\perp}}\left[\mathcal{A}^2+k_\perp\cdot k'_\perp\right] \\ &+ e_{\bar{q}_2}\int\{dx\}\frac{\phi_P(x,k_\perp)}{\sqrt{\mathcal{A}^2+k_\perp^2}}\frac{\phi_{P'}(x,k''_\perp)}{\sqrt{\mathcal{A}^2+k''^2_\perp}}\left[\mathcal{A}^2+k_\perp\cdot k''_\perp\right], \end{aligned} \tag{20}$$

where $k'_\perp = k_\perp + xQ_\perp$, $k''_\perp = k_\perp-(1-x)Q_\perp$. From Eqs. (6), (7), and (9), it is understandable that the term $\sqrt{\mathcal{A}^2+k_\perp^2}$ comes from the Melosh transformation. After fixing the parameters which appear in the wave fnction, Eq. (20) can be used to fit the experimental data. But this is not the whole story. We consider the term $\widetilde{\phi}_P \equiv \phi_P(x,k_\perp)/\sqrt{\mathcal{A}^2+k_\perp^2}$ and take the Tayor expansion around $k_\perp^2$

$$\widetilde{\phi}_{P'}(k'^2_\perp) = \widetilde{\phi}_{P'}(k^2_\perp) + \left.\frac{d\widetilde{\phi}_{P'}}{dk_\perp^2}\right|_{Q_\perp=0}(k'^2_\perp-k^2_\perp) + \left.\frac{d^2\widetilde{\phi}_{P'}}{2(dk_\perp^2)^2}\right|_{Q_\perp=0}(k'^2_\perp-k^2_\perp)^2 + ... \tag{21}$$

Then, by using the idenity

$$\int d^2k_\perp\ (k_\perp\cdot A_\perp)(k_\perp\cdot B_\perp) = \frac{1}{2}\int d^2k_\perp\ k_\perp^2\ A_\perp\cdot B_\perp, \tag{22}$$

we can rewrite (20) to

$$\begin{aligned} F_P(Q^2) &= (e_{q_1}+e_{\bar{q}_2}) \\ &+ Q^2\int\{dx\}\,\phi_P^2(x,k_\perp)[x^2e_{q_1}+(1-x)^2e_{\bar{q}_2}]\left(\Theta_P\frac{\mathcal{A}^2+2k_\perp^2}{\mathcal{A}^2+k_\perp^2}+\widetilde{\Theta}_P k_\perp^2\right) \\ &+ \mathcal{O}(Q^4), \end{aligned} \tag{23}$$

where

$$\Theta_M = \frac{1}{\widetilde{\phi}_M}\left(\frac{d\widetilde{\phi}_M}{dk_\perp^2}\right),\quad \widetilde{\Theta}_M = \frac{1}{\widetilde{\phi}_M}\left(\frac{d^2\widetilde{\phi}_M}{(dk_\perp^2)^2}\right). \tag{24}$$

The mean square radius

$$\langle r^2\rangle_P \equiv -6\left.\frac{dF_P(Q^2)}{dQ^2}\right|_{Q^2=0} \tag{25}$$

can be obtained easily that

$$\begin{aligned}
\langle r^2\rangle_P &= \langle r^2\rangle_{q_1} + \langle r^2\rangle_{\bar q_2} \\
&= e_{q_1}\Big\{ -6\int\{dx\} x^2 \widetilde{\phi}_P \Big[(\mathcal{A}^2+2k_\perp^2)\frac{d}{dk_\perp^2} + (\mathcal{A}^2+k_\perp^2)k_\perp^2\Big(\frac{d}{dk_\perp^2}\Big)^2\Big]\widetilde{\phi}_P\Big\}, \\
&+ e_{\bar q_2}\Big\{ -6\int\{dx\}(1-x)^2 \widetilde{\phi}_P \Big[(\mathcal{A}^2+2k_\perp^2)\frac{d}{dk_\perp^2} + (\mathcal{A}^2+k_\perp^2)k_\perp^2\Big(\frac{d}{dk_\perp^2}\Big)^2\Big]\widetilde{\phi}_P\Big\}. \qquad (26)
\end{aligned}$$

It is worthwhile to mention that, first, the static property $F_P(0) = e_P$ is quite easily checked in (23). Secondly, from Eq. (26), we find that the mean square radius is related to the first and second longitudinal momentum square derivatives of $\widetilde{\phi}$ which contain the Melosh transformation effect.

3 Heavy Quark Limit

In this section, we will check the HQS among the EM form factors by taking the heavy quark limit. To proceed, we first investigate the heavy-quark-limit behavior of the wave function. In the infinite quark mass limit $m_Q \to \infty$, the light-front wave function has the scaling behavior [25]:

$$\phi_{Q\bar q}(x,k_\perp) \to \sqrt{m_Q}\,\Phi(m_Q x, k_\perp), \qquad (27)$$

where the factor $\sqrt{m_Q}$ or $\sqrt{M}$ (M being the mass of the heavy meson) comes from the particular normalization we have assumed for the physical state in (10-11). The reason why the light-front heavy-meson wave function should have such an asymptotic form is as follows. Since x is the longitudinal momentum fraction carried by the light antiquark, the meson wave function should be sharply peaked near $x \sim \Lambda_{\rm QCD}/m_Q$. It is thus clear that only terms of the form "$m_Q x$" survive in the wave function as $m_Q \to \infty$; that is, $m_Q x$ is independent of m_Q in the $m_Q \to \infty$ limit. For the Gaussian-type wave function (12), we obtain

$$\Phi(X,k_\perp)_{\rm G} = 4\left(\frac{\pi}{\omega^2}\right)^{3/4} \exp\left(-\frac{k_\perp^2}{2\omega^2}\right)\exp\left(-\frac{(\frac{X}{2}-\frac{m_{\bar q}^2+k_\perp^2}{2X})^2}{2\omega^2}\right)\sqrt{\frac{1}{2}+\frac{m_{\bar q}^2+k_\perp^2}{2X^2}}, \qquad (28)$$

where $X \equiv m_Q x$. The normalization of the meson state (10) becomes

$$\langle M(v')|M(v)\rangle = 2(2\pi)^3 v^+ \delta^3(v'-v) \qquad (29)$$

where $P = m_M v$ and $|M(v)\rangle = m_M^{-1/2}|M(P)\rangle$, thus the normalization condition (11) becomes

$$\int_0^\infty dX \int \frac{d^2k_\perp}{2(2\pi)^3}\,|\Phi(X,k_\perp)|^2 = 1. \qquad (30)$$

For decay constant, the definition (16) become

$$\langle 0|\bar q\gamma_\mu\gamma_5 Q|P(v)\rangle = i\,\bar f_P\, v_\mu, \qquad (31)$$

respectively. We find, after taking the heavy quark limit,

$$\bar{f}_P = 4\frac{\sqrt{3}}{\sqrt{2}} \int \frac{dX\, d^2k_\perp}{2(2\pi)^3}\, \Phi(X, k_\perp)\, \frac{X + m_{\bar{q}}}{\sqrt{(X + m_{\bar{q}})^2 + k_\perp^2}}. \tag{32}$$

For the mean square radius Eqs. (26), when the heavy quark limit is considered, we get

$$x \to \frac{X}{m_Q}, \quad \mathcal{A} \to \widetilde{\mathcal{A}} \equiv X + m_2, \tag{33}$$

and obtain

$$\langle r^2 \rangle_P = \langle r^2 \rangle_Q + \langle r^2 \rangle_{\bar{q}_2}, \tag{34}$$

where

$$\begin{aligned} \langle r^2 \rangle_Q &= e_Q \Big\{ \frac{-6}{m_Q^2} \int \frac{dX d^2k_\perp}{2(2\pi)^3} X^2 \widetilde{\Phi} \Big[(\widetilde{\mathcal{A}}^2 + 2k_\perp^2) \frac{d}{dk_\perp^2} + (\widetilde{\mathcal{A}}^2 + k_\perp^2) k_\perp^2 \Big(\frac{d}{dk_\perp^2} \Big)^2 \Big] \widetilde{\Phi} \Big\} \\ &\to 0, \end{aligned} \tag{35}$$

$$\langle r^2 \rangle_{\bar{q}_2} = e_{\bar{q}_2} \Big\{ -6 \int \frac{dX d^2k_\perp}{2(2\pi)^3} \widetilde{\Phi} \Big[(\widetilde{\mathcal{A}}^2 + 2k_\perp^2) \frac{d}{dk_\perp^2} + (\widetilde{\mathcal{A}}^2 + k_\perp^2) k_\perp^2 \Big(\frac{d}{dk_\perp^2} \Big)^2 \Big] \widetilde{\Phi} \Big\}, \tag{36}$$

and $\widetilde{\Phi} = \Phi / \sqrt{\widetilde{\mathcal{A}}^2 + k_\perp^2}$. Eq. (35) means that the mean square radius $\langle r^2 \rangle_P$ is blind to the flavor of Q. This is the so-called flavor symmetry. We find that the light degrees of freedom are blind to the flavor of the heavy quark. In addition, [26] find the mean square radius also satisfied the spin symmetry. These are the so-called HQS. Up to now, we have not uesd the wave function yet, this also satisfies the well-known property that HQS is model-independent. Reviewing the processes, we can realize that, in this approach, the static properties of the EM form factors and the heavy quark symmetry of the mean square radii can be checked much more easily than in the Breit frame. This is the major reason why we calculate the Q^2 dependence of those form factors order by order.

4 Numerical Results

In this section, we will use the Gaussian-type wave function (12) to calculate the EM from factors, mean square radius. The parameters appearing in the wave function, the quark mass m_q and the scale parameter ω, are constrained by the decay constants.

The decay constants of pseudoscalar mesons π, K, and D_s come from the experiments [27]

$$f_\pi = 130.7 \text{ MeV}, \quad f_K = 159.8 \text{ MeV}, \quad f_{D_s} = 280 \text{ MeV}, \tag{37}$$

the others are obtained by model calculations and lattice results

$$f_D = 192 \text{ MeV}[28], \quad f_B = 157 \text{ MeV}[28], \quad f_{B_s} = 171 \text{ MeV}[28], \quad f_{B_c} = 360 \text{ MeV}[29]. \tag{38}$$

Combining with the quark masses

$$m_{u,d} = 0.24 \text{ GeV}, \quad m_s - m_{u,d} = 0.18 \text{ GeV}, \quad m_c = 1.6 \text{ GeV}, \quad m_b = 4.8 \text{ GeV}, \tag{39}$$

we fit the scale parameters

$$\begin{aligned} &\omega_\pi = 0.333 \text{ GeV}, \quad \omega_K = 0.379 \text{ GeV}, \quad \omega_D = 0.443 \text{ GeV}, \quad \omega_{D_s} = 0.606 \text{ GeV}, \\ &\omega_B = 0.477 \text{ GeV}, \quad \omega_{B_s} = 0.485 \text{ GeV}, \quad \omega_{B_c} = 0.813 \text{ GeV}. \end{aligned} \tag{40}$$

The Q^2-dependence behaviors of F_π and F_K can be obtained by Eq. (20). We compare the results with the data in Fig. 1 and 2, respectively. In addition, the mean square radii of the pseudoscalar meson can be obtained by Eq. (26). We list the results of the $\langle r^2 \rangle_{\pi^+,K^+,K^0}$ and the experimental data in Table 1. (the unit is fm^2)

$\langle r^2 \rangle$	π^+	K^+	K^0
this work	0.443	0.349	-0.0676
[11]	0.314	0.240	-0.020
[12]	0.452	0.38	0.057
experiment	0.439 ± 0.008 [1]	0.34 ± 0.05 [5]	-0.054 ± 0.026 [7]

Table 1. The mean square radii of the π^+, K^+, and K^0 mesons.

The negative sign is interesting, and may be interpreted as the preponderance of negative electric charge in the tail of the distribution. We find these values are all consistent with the data. The mean square radii of the other pseudoscalar meson are list in Table 2.

	D^+	D^0	D_s^+	B^+	B^0	B_s^0	B_c^+
$\langle r^2 \rangle$	0.184	-0.304	0.0831	0.378	-0.187	-0.119	0.0433

Table 2. The mean square radii of the other pseudoscalar mesons.

5 Conclusion

We have calculated the EM form factors of the pseudoscalar mesons. The EM form factors are extracted from the relevant matrix elements directly, instead of choosing the Breit frame. We found that the charge radius is related to both the first and second longitudinal momentum square derivative of the momentum distribution function. We also found the static properties of the EM form factors and the heavy flavor symmetry of the mean square radii are checked analytically by evaluating the Q^2 dependence of those form factors order by order. Therefore, in the heavy quark limit, the charge radii of pseudoscalar have flavor symmetries, and these properties are model-independent. In addition, The Q^2-dependence behaviors of the form factors $F_{\pi,K}$ and the mean square radius of light and heavy mesons have been calculated by using the Gaussian-type wave function. The predictive values are all consistent with the current experimental data.

ACKNOWLEDGMENTS

This work was supported in part by the National Science Council of ROC under Contract No. NSC90-2112-M-007-040.

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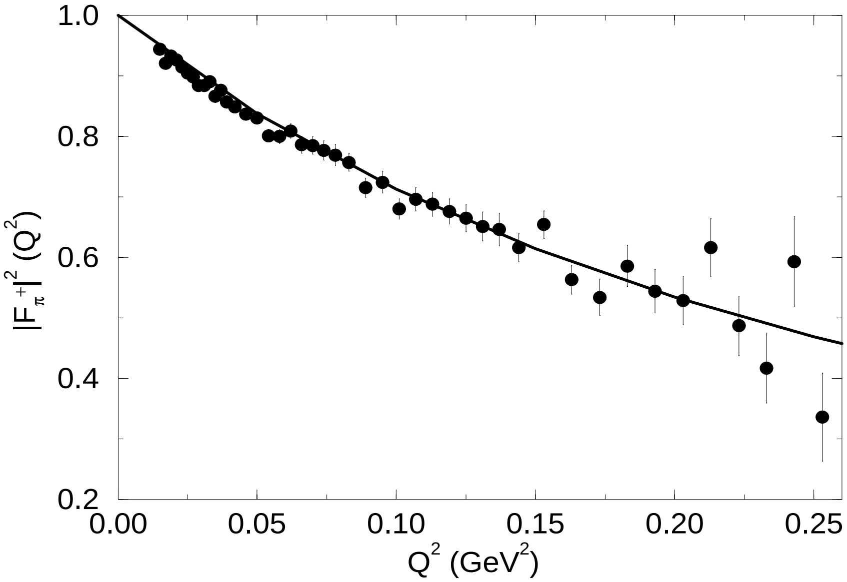
FIGURE CAPTIONS

Fig. 1 The charge form factor of the pion in small momentum transfer. Data are taken from [1].

Fig. 1 The charge form factor of the Kaon in small momentum transfer. Data are taken from [5].


1.0
0.8
0.6
0.4
0.2
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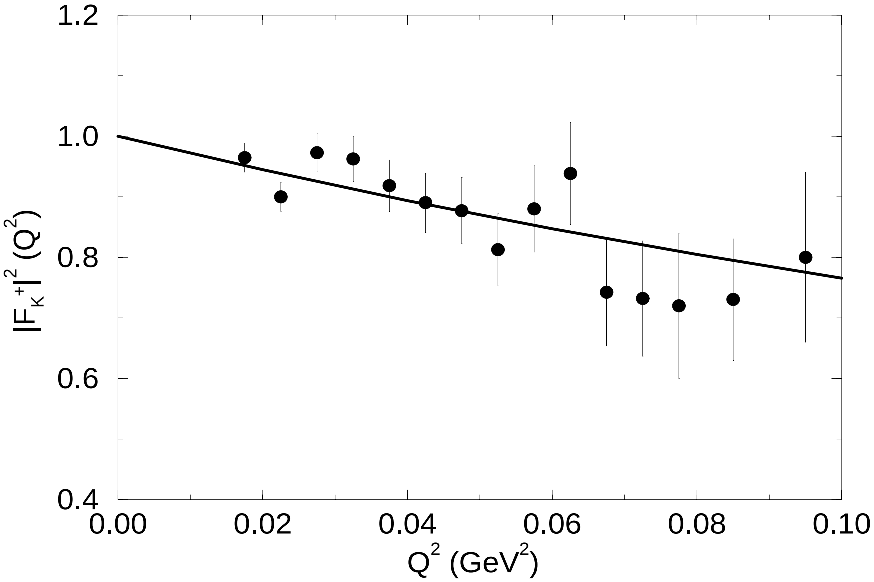
0.15
0.20
0.25
Q^2 (GeV^2)
|F_π^+|^2 (Q^2)


1.2
1.0
0.8
0.6
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0.02
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$|F_{K^+}|^2\,(Q^2)$
Q^2 (GeV^2)